Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews 13 (2009) 462–472
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Solar thermal heat engines for water pumping: An update

Agustín M. Delgado-Torres *

Dpto. Física Fundamental y Experimental, Electrónica y Sistemas, Universidad de La Laguna, Avda. Astrofísico Francisco Sánchez s/n, 38205 La Laguna, Tenerife, Spain

Received 16 August 2007; accepted 7 November 2007

Abstract

Solar thermal-driven heat engines for water pumping have been previously reviewed for some authors in the past century. However, some devices have not been treated as metal hydride-based systems or the pumping subsystems of solar thermal-driven reverse osmosis desalination systems. Following the typical classification given in the previous literature, in this work an update of the solar heat engines for water pumping based in thermodynamic methods (conventional and unconventional) is presented. Besides small remarks about systems previously quoted by other authors, new designs found in the literature are described. In general, the main characteristics of these systems is their low efficiency, low power output and, in the case of unconventional designs, its simplicity. This work in conjunction with previous review papers make up reference point for the knowledge of the use of solar thermal energy for liquid pumping purpose.

Keywords: Solar heat engines; Solar thermal energy; Water pumping; Solar thermal reverse osmosis desalination; Solar desalination

Contents

1. Introduction

Solar water pumping is a process that can be carried out with direct conversion methods or with thermodynamic methods [1]. In the first case, solar energy turns into electric energy so the produced electric current drives the conventional pump's motor. As for the thermodynamic methods, its operation principle is the conversion of thermal energy into work by means of power cycles (gas or vapour) or hydrogen adsorption/desorption cycles. Once the thermo-mechanical conversion has been carried out there are two alternatives: (1) the mechanical energy generated drives a conventional pump (conventional thermodynamic method, CTM) and (2) the mechanical energy generated drives a specially designed water pumping system (unconventional thermodynamic method, UTM). The operation scheme of a solar thermal heat engine for water pumping purpose by means of the thermodynamic conversion of heat into work is given in Fig. 1 [2]. Thermal energy obtained from

* Tel.: +34 922318102; fax: +34 922318228.
E-mail address: amdelga@ull.es.

1364-0321/$ – see front matter
doi:10.1016/j.rser.2007.11.004

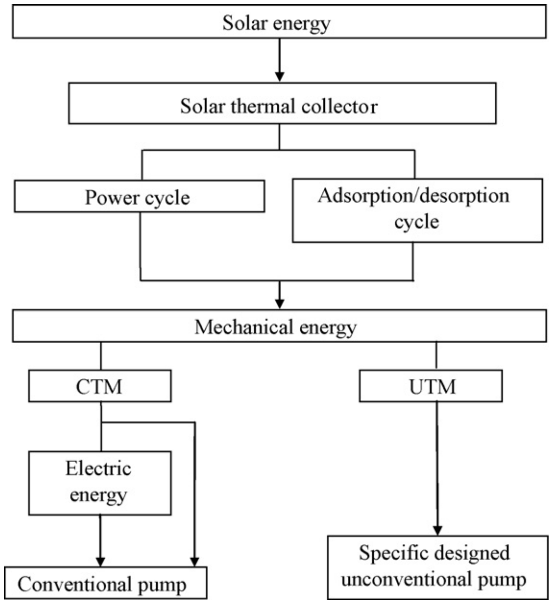

Fig. 1. Scheme of the water pumping process by means of solar thermal-driven thermodynamic methods (CTM, conventional thermodynamic method; UTM, unconventional thermodynamic method) [2].

the solar radiation with a solar collector is the energy source of the process.

Solar thermal heat engines based in thermodynamics methods have been reviewed previously by Pytlinski [3], Butti and Perlin [4], Mankbadi and Ayad [5], Spencer [6–8] and Wong and Sumathy [9]. In a previous paper, a review of solar thermal-driven reverse osmosis desalination systems has been published [2]. In these systems, a solar heat engine that fits to a CTM is used to pressurize the feedwater of the reverse osmosis unit. Due to the similarity between the operational schemes of such systems with the solar heat engines for irrigation or human use purpose, some information given in the review of Delgado-Torres and García-Rodríguez [2] can be considered as an additional contribution to the knowledge of the solar heat engines designed or proposed for liquid pumping. As well as the aforementioned, additional designs of solar heat engines for water pumping fitted to a CTM scheme that are not quoted by previous review papers [3–9] were quoted by Delgado-Torres and García-Rodríguez [2]. The main objective of this paper is the update of the systems and knowledge about solar heat engines for water pumping, mainly in the case of UCT-based systems not covered by Delgado-Torres and García-Rodríguez [2]. This work is a summary of a part of the academic thesis of the author [10].

2. Conventional thermodynamic methods (CTM)

In this paper the information about the outstanding CTM solar thermal heat engines is summarized in Tables 1–3.

Most designs of solar thermal heat engines for water pumping based on the CTM scheme developed before I World War are quoted in Table 1. The research on these systems dates from second half of the 19th century with the works of Augustin Mouchot and Abel Pifre. These researchers used as solar thermal systems truncated cones with copper tubes placed along its axis acting as boilers between 1865 and 1880. In the case of an improved design of Mouchot with a reflecting area of 4 m^2 and with a boiler 0.8 m long [3], a similar system was used to drive the engine of a water pump. According to Butti and Perlin [4], this should be held in Argelia in 1877 or 1878. In 1878, A. Mouchot – with the help of A. Pifre – builds a solar thermal heat engine with conical reflector. A. Pifre gives the description of another system in 1880 (see Table 1).

At the beginning of 20th century the systems developed by Aubrey Eneas and Frank Shuman stands out. A. Eneas began using parabolic collectors for the design of solar heat engines. As a consequence of certain technical problems, this initiative was given up later and the truncated conical reflector geometry was adopted as A. Mouchot had previously done. The system of A. Eneas – publicly exhibited in 1901 – ran in a satisfactory way during 2 years and it is described in Table 1. The main disadvantage of this design was of economic nature, since the power output unit cost was between two and five times greater than the cost obtained in a conventional power plant [4].

Another system quoted in Table 1 was developed by Willsie and Boyle in 1905. This system was modified sometimes until the final version of 1908. This last version included two modifications with respect to the original design: (1) the solar field was consisted of single-glazed and double-glazed solar collectors and (2) the hot water from the solar collectors was conducted toward a storage tank so the water pumping could be made even at night time [6].

In relation to F. Shuman's works, at the beginning this researcher used wooden boxes to attain the solar radiation concentration so he knew the economic disadvantages of using reflectors. In 1907, F. Shuman uses the wooden boxes technology to drive a low temperature solar heat engine for water pumping. The description of such system is given in Table 1. Subsequently, this system was modified for increasing the power output but without an increasing of its cost. With this purpose, besides wooden boxes reflector plates were used, metallic elements for heat absorption were put into the boxes and the insulation was improved. Also, a device for the adjustment of collector's tilt once per 3 weeks according to Butti and Perlin [4] and once a week according to Pytlinski [3] was installed. The characteristics of this system that started to run in 1911 are given in Table 1. Later, F. Shuman made some modifications changing the concentrators aforementioned by parabolic-section concentrators in which axis copper covered tubes were placed acting as boilers. This system was built in Meadi (Egypt) in 1912 and its characteristics and performance results obtained in 1913 are also given in Table 1.

The outbreak of the I World War and the beginning of using the fossil fuels made the research on solar heat engines and their applications decline. The only one reference found about a solar heat engine for water pumping in the interwar period dates from year 1920 with the system of J.A. Harrington [6].

Some solar thermal water pumping systems designed after the II World War are given in Tables 2 and 3. It must be pointed out the work made by the French company Sofretes in the 1970s. In addition, Youm et al. [11] quote the installation and

Table 1
Solar thermal heat engines for water pumping according to the CTM scheme developed before the I World War

Year and location	Solar collector	Thermodynamic cycle/working fluid(s)	Pumping system characteristics
1878 [4], Paris (France)	Solar collector with conical reflector	Rankine/water	A column formed by interconnected vertical tubes was placed along the cone axis. Pumping capacity of 2.2 m^3/h
1880 [3], Paris (France)	Parabolic collector with 9.2 m^2 aperture area	Rankine/water	Rotative pump which lift 0.1 m^3 at a discharge head of 3 m in 14 min
1901 [3,4]; Pasadena, California, (E.E.U.U.)	Truncated cone with sun tracking. 10 m diameter and 4.5 m diameter in the bottom. Inner surface formed by approximately 1800 flat mirrors [3,4]	Rankine/water	Steam generated at 1.03 MPa. This vapour drives an 8.085 kW engine coupled to a centrifugal pump. For a pumped flow of 5.3 m^3/min at a discharge head of 3.6 m the power delivery by the system is 7.35 kW [3]. Pumping of 6.4 m^3/min from a tank at 5 m depth [4]
1905 [3]	Flat plate collector	Rankine/sulphur dioxide	Vapour generated at 13.8 bar that drives a 14.7 kW engine connected to a centrifugal pump
1907 [3,4], Pensilvania (E.E.U.U.)	Solar pond of 11.2×10^3 m^2 area glass-covered [3]; wooden box of 100 m^2 [4]	Binary/water; Rankine with ether	Ether vapour generated in the water-submerged heat exchanger drives a 2.57 kW vapour engine connected to a small centrifugal pump [3,4]
1911 [3,4], Pensilvania (E.E.U.U.)	Wooden boxes with reflector plates for concentration; total aperture area around 1000 m^2	Rankine/water	The system lifts 11.3–12 m^3/min at a discharge head of 10 m. It delivers a maximum power of 17.64–23.52 kW and a mean daily power of 10.29–11.76 kW [3,4]
1913 [3,4], Meadi (Egypt)	Five parabolic trough collectors 60 m long and 4 m wide each, approximately [3,4]	Rankine/water	The system pumps 27 m^3/min and delivers a maximum power of 40.42 kW [4]

performance of six solar thermal water pump systems with powers between 1 kW and 30 kW in Senegal at the end of 1970s. The system installed in Universidad Nacional Autonoma de Mexico (UNAM) was developed in the framework of the investigations made by this institution in the field of direct steam generation with parabolic trough solar collectors [12].

The 150 kW system built in Coolidge (Arizona, E.E.U.U.) is considered in this paper as the best documented solar thermal water pumping system based in a CTM scheme. This system began its operation in 1979 until 1982 and its design laid in the experience of previous plants installed in Gila Bend (Arizona, E.E.U.U.) and Willard (New Mexico, E.E.U.U.) (see Tables 2 and 3). Abundant information about Coolidge Solar Irrigation Project can be found in Ref. [13–17].

As it has been said in Section 1, another type of systems quoted in this paper are the solar thermal-driven reverse osmosis systems reviewed by Delgado-Torres and García-Rodríguez [2]. Besides the systems which use solar ponds as solar thermal systems in El Paso and Los Baños (E.E.U.U.), two experiences with Sofretes systems were carried out in France and Egypt (see Table 3). Manolakos et al. [18] have made the first experimental evaluation of the solar organic Rankine system but without connecting it yet to the high-pressure pump of the desalination unit.

Some experiences has been carried out in India and Iran with the main objective of provide water pumping methods for farms located far from the grid and in semiarid regions. In this paper the works of Spindler et al. [19], Chandwalker and Oppen [20] and Aghamohammadi et al. [21] are pointed out (see Table 3). Zeller [22] makes a theoretical study of the performance of the system of Chandwalker and Oppen [20] under the solar radiation conditions and water demand in the Indian region of Andhra Pradesh. He makes the cost comparison of this system with the cost of the pumped water by means a solar photovoltaic water pumping system.

As can be observed in previous tables, Rankine cycle – usually with water or an organic compound as working fluids – and also a binary cycle with water as heat transfer fluid in the top cycle and an organic compound in a bottom Rankine cycle are the common power cycles used in the CTM.

3. Unconventional thermodynamics methods (UTM)

The development of solar thermal heat engines for water pumping whose operation fits to a UTM has been less noticeable than the systems based in CTM. The operation principle of these systems is almost the same in all the designs found in the literature reviewed, identifying three variants: (1) the heating and evaporation of a working fluid causes the water pumping whereas the subsequent vapour condensation causes the suction of the liquid from the well or vessel from which is extracted, (2) the alternative heating and cooling of a gas causes the pumping and suction of the water to be lifted and (3) the heating of a chemical compound causes the generation of a gas at a pressure that permits the water pumping whereas the

Table 2
Solar thermal heat engines for water pumping according to the CTM scheme developed between 1954 and 1977

Year and location	Solar collector	Thermodynamic cycle/working fluid(s)	Pumping system characteristics
1954 [9]	Parabolic collector	Ericsson/air	A hot air engine drives a small pump which lifts water from 4.8 m depth
1962–1966 [23], Dakar (Senegal)	Flat plate collector 6 m^2 aperture area	Binary/water; Rankine	Engine connected to a turbo-alternator. The electrical current generated drives a conventional pump. The system was capable of pump 8–10 l/min from 13 to 14 m in depth
1967 [3], Mali (Africa)	–	Binary/water; Rankine with chlorobenzene	The mechanical energy produced with a turbine was consumed by a centrifugal pump that lifts 11.3 m^3/day at a discharge head of 45.7 m
1975 [21], San Luis Delapaz (Mexico)	–	–	25 kW SOFRETES system that pumps 2.5 m^3/day
1976 [21]; Egypt, India, Brazil, Senegal, Mali, Mauritania and Nigeria	Flat plate collector of 100 m^2 aperture area	–	SOFRETES system capable of pump 30 m^3/day at a discharge head of 20 m. The pumping system is consisting of a two-cylinder expansion engine, a hydraulic press and a diaphragm pump
1976 [9], Guanajuato (Mexico)	Flat plate collectors of 2499 m^2 aperture area	Binary/water; Rankine with R11	SOFRETES system with vapour turbine coupled to an electric generator that drives two pumps. Pumped flow: 1000 m^3/day
1976 [12], UNAM (Mexico)	Only parabolic trough collector initially and additional flat plate collectors and evacuated tube collectors subsequently	Rankine/water	Initially a 1 kW pump was connected to a turbine and to a two-piston steam engine later. Global efficiency around 2%
1977 [21], North of Iran	–	–	Three SOFRETES units
1977 [9], Gila Bend, Arizona (E.E.U.U.)	Parabolic trough collector. Total aperture area: 554 m^2	Binary/water; Rankine with R113	Centrifugal pump. Pumping capacity of 38 m^3/min
1977 [9], Willard, Nuevo México, E.E.U.U.	Parabolic trough collector. Total aperture area: 622.4 m^2	Binary/Caloria HT-43; Rankine with R113	Centrifugal pump. 2.6 m^3/min from a well 34 m depth.

cooling of the chemical compound induces the adsorption of the gas and a pressure reduction occurs. This pressure reduction is used for the water suction from a lower level. The latter is the operation principle of metal hydride-based systems, not quoted in previous review papers [3–9].

Depending on the cooling way of the pump, one can distinguish between solar thermal air-cooled pumping system and solar thermal water-cooled pumping systems [25]. In the second one, the previous pumped water acts as cooling medium being this the more common way.

In the following sections, UTM-based designs found in the literature and not quoted in the review papers [3,5,8,9] are described besides small remarks about some designs already quoted by previous authors.

3.1. Vapour cycles based systems

As it has been aforementioned, A. Mouchot is one of the researchers with major interest in solar heat engines and its application to water pumping in the second half of 19th century. In this paper, we consider his system patented in 1861 and quoted by Butti and Perlin [4] as the first UTM-based solar thermal heat engine for water pumping.

In the past century, Jenness [26] proposes a Savery engine-based pumping system in which the inlet of saturated vapour in a tank induces the displacement of the liquid water. The subsequently vapour cooling and condensation entails a pressure drop inside the tank that causes the suction of the liquid from a lower level to the tank. The saturated vapour generation takes place in a boiler where the solar radiation is concentrated. According to a similar operation principle is the performance of the called ‘‘thermopumps’’ in the literature. Wong and Sumathy [9] and Mankbadi and Ayad [5] quote some designs of this type, being one of them the Maccracken’s thermopump. In this system, the vapour presses a float and as a result the water is pumped. There are some designs similar to the latter but without using the float [5].

A system thought for its possible use in African countries has been developed in United Kingdom and has been proposed by Picken et al. [27]. The system (see Fig. 2) has been tested with 2 m^2 aperture area of evacuated tube heat pipe solar collectors. The solar collector system is connected to a specific designed positive displacement pump. In this pump, the generated vapour displaces the liquid water in the cylinder A and begins its condensation when the water level gets the end of said cylinder.

Table 3
Solar thermal heat engines for water pumping according to the CTM scheme developed after 1977

Year and location	Solar collector	Thermodynamic cycle/working fluid(s)	Pumping system characteristics
1979–1982 [13–17]; Coolidge, Arizona, E.E.U.U.	Parabolic trough collectors. Total aperture area: 2140 m^2	Binary/Caloria HT-43; Rankine with toluene	Grid connected system. Single stage impulse turbine, gear reduction unit, synchronous generator
1978 [10], Cadarache (France)	–	–	3 kW SOFRETES system
1981 [10], El Hamrawin (Egypt)	Flat plate collectors. Total aperture area: 384 m^2	Binary/water; Rankine with R11	10 kW SOFRETES system
1983 [24]	4 flat plate collectors of 1 m^2 aperture area each	Rankine/R113	Diaphragm pump. 14.6 l/min at 3 m with a mean solar irradiance of 850 W m^{-2}
1986 [19], India	Flat plate collectors of 7 m^2 total aperture area	Rankine/R11	Global daily efficiency of 0.45% with a peak around 0.7%. Pumping of 6.5 m^3/day from a well 11.2 m deep.
1987 [7], India	6 parabolic collectors 9 m in diameter	Rankine/water	Generation of steam at 500 °C and 7 MPa to drive a 20 kW steam engine connected to irrigations pumps
1987 [7], Ghana	Parabolic trough collector	Rankine/water	Two installations, one with a submerged pump and another with a liquid piston pump for surface water
1987 [7], India	Flat plate collector	Organic Rankine Cycle	The organic vapour drives an engine coupled to a submerged pump. Efficiency slightly greater than 2%
1996 [19]; India, Germany	Parabolic collector of 2 m^2 aperture area	Rankine/R113	Double effect piston pump. System built in India and tested in Germany
2001 [21]; Khafr, Iran	Flat plate collector	Binary/water; Rankine with R114	Yearly simulations give mean pumped flow values of 20 m^3/day, and an efficiency of 2.8%
2001 [20], India	Parabolic	Organic Rankine cycle	Double effect (action) piston engine coupled to a pump. The system is capable of pump 2 m^3/day at 6 m discharge head with a global efficiency around 2.5%

As can be observed, in this design direct contact between the water to be pumped and the vapour generated with the solar thermal system exists. The vapour condensation inside the cylinder sets out some problems. Picken et al. [27] propose improving the design of the cylinder A and the use of a pressure maintain valve for its solution. The tests carried out with this system gives a lifted flow between 9 l/h and 22 l/h for discharge heads between 1 m and 8 m and an average solar irradiance value of 800 W/m^2. The global efficiency of the system is very slow, around 0.05%.

Another kind of system designs are the two proposed by Rao and Rao [25]. Both systems are based in a principle similar to aforementioned thermopumps, run with flat plate solar collectors and use pentane as working fluid. The Brown

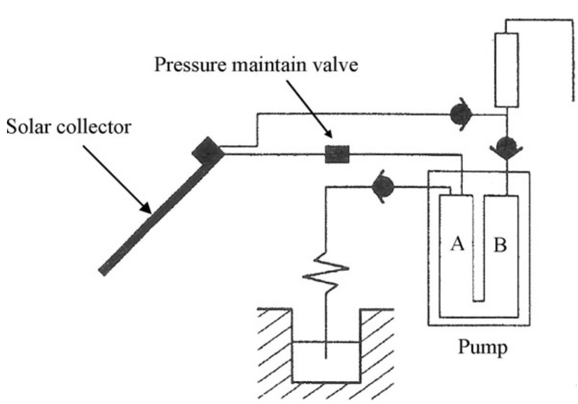

Fig. 2. System of Picken et al. [26].

Boveri system quoted by Mankbadi and Ayad [5] and by Wong and Sumathy [9] with pentane as working fluid is a water-cooled design very similar to Rao and Rao system [25].

In some designs, the utilization of rubber flexible membranes or diaphragm and bellows has been considered to avoid the problem of the direct contact between the working fluid and the water to be pumped. In this paper the designs quoted by Wong and Sumathy [9], the design of Sharma and Singh [28] and the proposal of Al-Haddad et al. [29] are pointed out.

The use of bellows and diaphragms in unconventional solar pumps has the advantage of simplicity and no mixing between the working fluid and the water to be lifted. However, due to the high maintenance cost of these devices, some designs with additional tanks full of air or water has been proposed in the literature. These additional tanks are situated between the working's fluid vapour and the tank where the water to be pumped is. Sudhakar et al. [30] propose a modification of the Rao and Rao [25] system. The Brown Boveri system quoted by Wong and Sumathy [9] is another example of these improved systems. The design is similar to the Sudhakar et al. [30] design with the exception of the float and also operates with pentane as working fluid.

The solar thermal water pump of Sumathy et al. [31] and Wong and Sumathy [32] is the best-reported UTM-based system. The main modification that this design introduces is the use of a solar vapour generated storage tank (see Fig. 3). The system with 1 m^2 aperture area of flat plate solar collector and pentane as working fluid was able to lift 336 l/day, 250 l/day

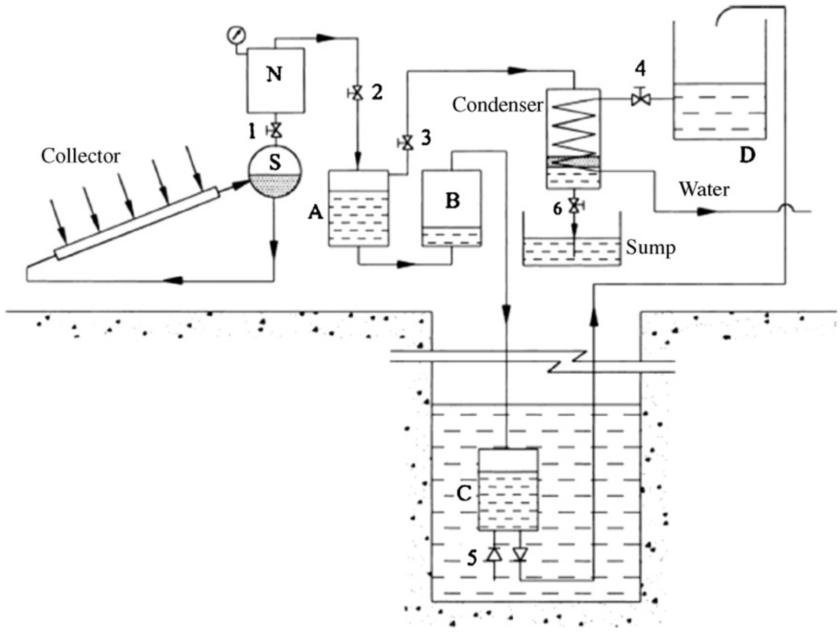

Fig. 3. System of Wong and Sumathy [31]. A, Water tank; B, air tank; C, well tank; D, overhead tank; N, vapour tank; S, separation tank.

and 170 l/day at 6 m, 8 m and 10 m respectively with a global efficiency between 0.12% and 0.14% [33]. In addition to the aforementioned measures, different analysis of specific aspects in the solar thermal pumping process like the condensation process [34] and the heat transfer in the solar collector [35,36] has been carried out. Also, theoretical studies on the system's performance with ethyl ether as working fluid instead of pentane indicates a better system efficiency [37,38].

In addition to the designs aforementioned so far, there are others as the Camel system [5] which operates with flat plate solar collectors and an organic fluid as working fluid or the Minto engine [1] invented by Wally Minto in 1975—whose operation is similar to the Camel system. This system has been recently studied by Quickenden et al. [39] from an experimental point of view with the main objective of improving its irregular operation. According to the authors, the latter could be one of the reasons because this pumping device has not been commercially established.

3.2. Liquid piston systems

Solar thermal water pumping systems based in the operation principle of the liquid piston engine also has been studied and proposed. Liquid piston engines are variants of the free-piston Stirling engine in which the solid piston and displacer have been replaced by a liquid. Solar thermal water pumping systems based in liquid piston systems are quoted by Wong and Sumathy [9] and by Mankbadi and Ayad [5]. In these systems, the oscillation of a U-shape liquid column causes the water lifting and suction. An example of this kind of solar pumps is the Fluydine system [5] in which the heating and cooling of an air mass gives the liquid column oscillation. In general, the main disadvantage of liquid piston system is its instability under changing loads.

Klüppel and Gurgel [40] and Klerk and Rallis [41] propose two devices based in a similar principle to the former that can be coupled to solar thermal collectors. In the system of Klüppel and Gurgel [40] (see Fig. 4) the alternative gas heating and cooling inside the main chamber as a consequence of getting in touch with hot and cold plates causes a gas pressure variation that produces the water pumping.

There is a displacer inside the chamber provoking the alternative contact of the gas with the cold and hot side of the engine. Klüppel and Gurgel [40] give the thermodynamic cycle described by the gas in the pumping process. They build a laboratory physical model working with air at 91.85 °C and 27.85 °C. There is direct contact between the gas and the water to be lifted in this design. As a consequence, it is observed that certain amount of gas is dissolved in the water after 1 h of pump's operation. This situation makes the pump's performance goes down. In addition, the operation of the system is very slowly which is due to the rate of heat transfer to the gas. Klüppel and Gurgel [40], with the objective of improving the system's efficiency, are working in a prototype in which this problem is overcome. They think that this system could operate coupled with solar collectors in Northeast regions of Brazil.

As for the device of Klerk and Rallis [41] (see Fig. 5), this system uses the gas heating and cooling inside two separated

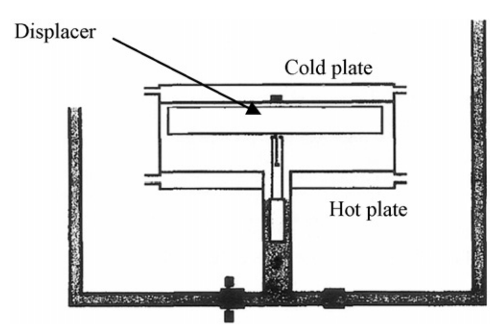

Fig. 4. Device proposed by Klüppel and Gurgel [39].

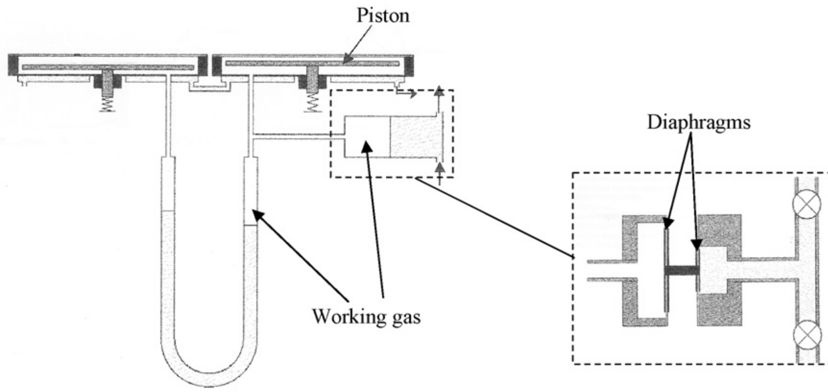

Fig. 5. Pumping system of Klerk and Rallis [40] with the pump's design pointed out.

chambers with mobile pistons. The temperature difference was of 35 °C in the tests carried out. The U-shaped pipe partially full of water is used for providing inertia to the system. The alternative heating and cooling of the working gas is carried out in similar devices to the Klüppel and Gurgel [40].

The pressure variation of the working gas causes the water pumping by means of a specific designed pump. This pump consists of two diaphragms of different area for the amplification of the pressure to apply over the water to be pumped and two non-return valves. The maximum power output of the system was attained in a dual mode operation, in other words, with the two displacer cylinders connected to the pump. In this configuration, the system was able to lift 54 l/h at 1 m. These operational results were obtained with an artificial heat source but the system is conceived for its performance with solar thermal energy [41].

Using the oscillation of a liquid column (usually water) to pump and suck water also has been used in designs in which the working fluid is the water steam generated from the column water itself. This steam is alternatively generated and condensed. A design of this kind is quoted by Wong and Sumathy [9] and by Mankbadi and Ayad [5] too.

As it has been aforementioned, one of the main disadvantages of the liquid piston type systems is its instability under changing loads. To avoid this, Orda and Mahkamov [42] describe some designs of the previous type with some elements and specific characteristics. These modifications permit a stationary operation of the system when the cycle parameters and the mechanical or hydraulic load have an important variability. In a first stage, a laboratory prototype is proposed and some experiments with electric heating were carried out. The maximum temperatures attained were between 75 °C and 95 °C and pressures of 80–160 kPa. For a power supplied of 0.8 kW, 2 kW and 3 kW a pump capacity of 0.5 m^3/h, 1.5 m^3/h and 2 m^3/h is obtained respectively whereas the thermal efficiency is between 0.2% and 0.5% [42]. Two different flat plate solar collectors were manufactured in the study of Orda and Mahkamov [42]. From the study of these solar collectors the conclusion is that, even if the efficiency of the solar collectors is too low in the mean temperature interval of operation of the pumping system, the solar collectors manufactured can supply the needed water temperature increasing for the pump's operation. With this information, Orda and Mahkamov [42] propose two designs – in addition to the first prototype – conceived for its operation with the solar collectors manufactured. The performance of one of these designs – that can be observed in Fig. 6 – is studied coupled with the two solar collectors.

In this system, the liquid oscillation in the hot and cold cylinders causes the piston displacement so that when the piston is descending the pumping of the water takes place thanks to the diaphragm action. When the piston rises the water is sucked from the lower level. With this system a pump capacity between 0.18 m^3/h and 0.65 m^3/h is obtained for solar irradiance values between 660 W/m^2 and 790 W/m^2.

The third design built can be observed in Fig. 7. This design is smaller than the previous ones and it has approximately the same pump capacity. Its operation is similar to the latter being the coaxial disposition of the hot and cold cylinder the main difference. With the selective coating solar collector with copper tubes and an average solar irradiance of 850 W/m^2 this system pumped 0.7 m^3/h at a discharge head of 1.5 m.

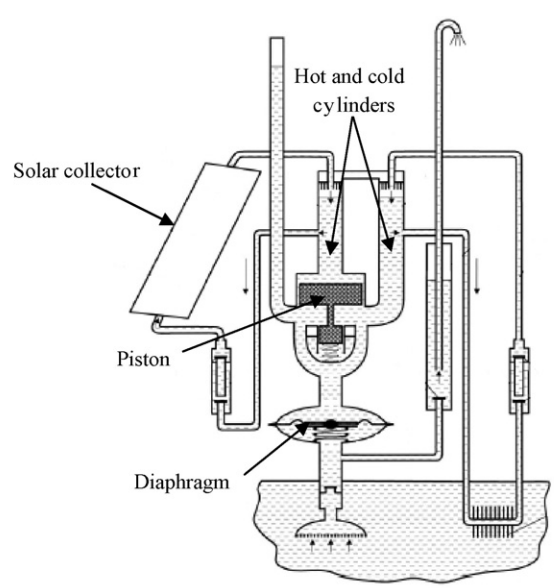

Fig. 6. Second laboratory prototype of Orda and Mahkamov [41].

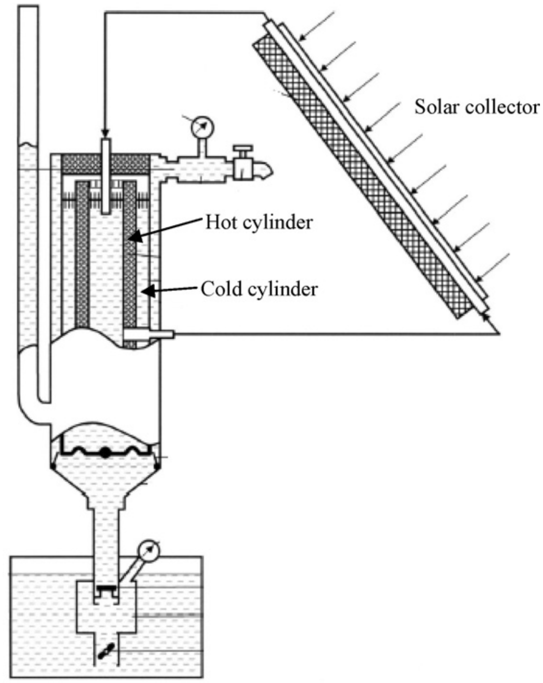

Fig. 7. Third prototype of Orda and Mahkamov [41].

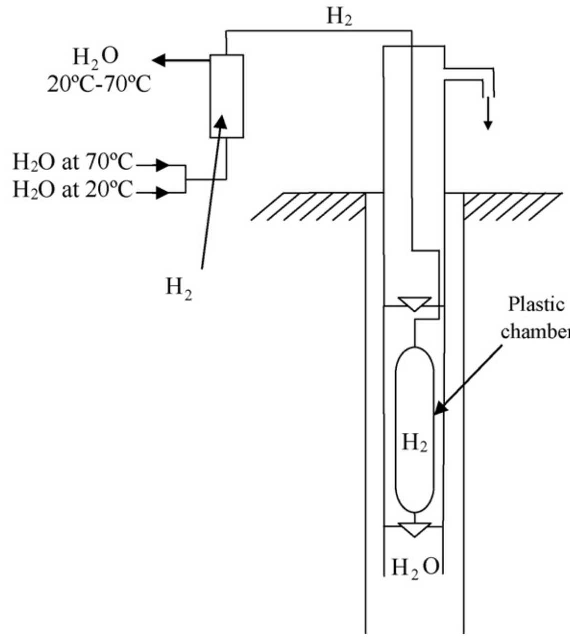

Fig. 8. Metal hydride-based system of Northrup and Heckes [42].

3.3. Metal hydride-based systems

The interest in metal hydride-based systems for water pumping dates from the end of the 1970s of the XX century. Just like most of the unconventional pumping systems, the interest in these devices is its possibility to become in cheap and simple water pumping systems that can be used in remote areas where the establishment of conventional systems is difficult or non-viable.

The operation principle of this system is the endothermic nature of the metal hydride dissociation reaction yielding hydrogen gas and the corresponding metal alloy. The other way around, hydrogen adsorption by the alloy takes place with a simultaneous heat generation. Hydrogen generation is due to the metal hydride heating at a temperature T_{de} so the hydrogen gas generated is in equilibrium with the alloy at a pressure p_{de}. The relation between T_{de} and p_{de} is given by the Van't Hoff equation so it is characteristic of the metal hydride in question. In the case of the metal hydrides treated in this paper, for a temperature $T_{de} = 70\ ^{\circ}C$ the equilibrium pressure does not exceed 500 kPa. The generation of the hydrogen gas causes the water lifting. On the other hand, the hydrogen adsorption by the alloy is an exothermic process. The heat generated is transfered to a cooling flow that, in general, is the water previously already pumped. When the hydrogen adsorption process by the alloy takes place at temperatures of 15 °C or 20 °C the equilibrium pressure is below 100 kPa in the systems quoted in this paper.

One of the first designs of a solar thermal metal hydride-based water pumping system was published by Northrup and Heckes [43]. The system was conceived for its operation with flat plate collectors. In this way, the windmills could be replaced as power sources for water pumping. The scheme of the design is in Fig. 8 where it can be observed that the system uses a flexible plastic chamber to isolate the hydrogen gas from the water to be pumped. In principle, the system was designed to pump water from a well at a depth of 60 m operating at temperatures of 80 °C and 20 °C. However, the operation of the system with solar collectors did not finish being the experiments carried out with hot water at 70 °C. The hydrogen generation due to the heating of the metal hydride provokes the chamber expansion and the water pumping while the hydrogen adsorption provokes the reduction of pressure inside the chamber and the water suction from the lower level. Thermal efficiencies of 1.63%, 2.03% and 2.4% were obtained with the laboratory scale model operating with temperatures between 68.3 °C and 23.0 °C for maximum pressure values of 208 kPa, 263 kPa and 334 kPa respectively while the theoretical

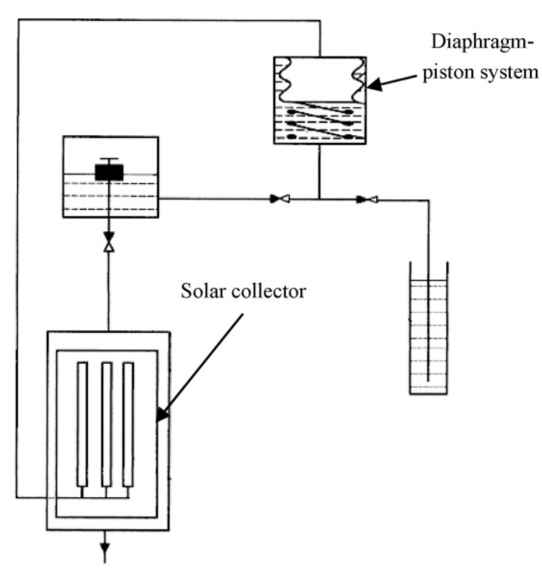

Fig. 9. Metal hydride-based design of Solovey and Frolov [43].

efficiency is around 6.8%. Northrup and Heckes [43] say that efficiencies of 4% or even 5% could be attained with this system if some improvements are made.

Solovey and Frolov [44] propose another design for its utilization with solar thermal energy. The metal hydride – based in 170 g of $LaNi_{4.6}Al_{0.4}$ alloy – is placed inside the absorber copper tubes of the solar collector (see Fig. 9).

These copper tubes are connected to the diaphragm-piston system. As metal hydride is heated, the generated gas can reach a pressure up to 300 kPa. This causes the piston displacement and the evacuation of the water from the tank A to the tank B. Once the water in the tank B has reached a certain level, the tank is automatically emptied and the water flows through the solar collector acting as cooling medium at temperatures between 15 °C and 20 °C. The cooling process provokes the hydrogen absorption by the alloy with the corresponding pressure reduction down to 40–70 kPa in the diaphragm. This reduction entails the water suction from the well or lower tank. In the tests carried out with electric heating this system was able to pump 800 l of water in 8 h of operation if the solar collector produces 232.2 W (200 kcal/h) of thermal energy [44].

The most interesting and complete study on a metal hydride-based solar thermal water pumping system is presented by Debashis and Gopal [45]. These authors make a simulation of the system of Fig. 10 and they analyze the effect of different design and operation parameters on the system performance.

This analysis is very important in relation to the solar pumping system viability so its initial costs mainly depends on the amount of metal hydride and the solar collector model used. The system operation is similar to the system of Solovey and Frolov [44] and just like that a flat plate collector is employed. The metal hydride is placed in the absorber tube, in the opposite side to the solar radiation incidence. The metal hydride temperature increasing as a consequence of solar insolation provokes the detachment of some hydrogen of the compound and the formation of hydrogen gas at the equilibrium pressure corresponding to the heating temperature. This gas causes the piston in the intermediate tank moves, driving the water inside to the tank on the top. When the piston finishes its stroke, automatically it is avoided that the already pumped water flows inside the solar collector so the absorption of previous generated hydrogen and a reduction of the pressure in the intermediate tank takes place. As a result, water is sucked from the well or the lower tank to the intermediate tank and the pumping cycle is finished. All the previous steps are carried out with a right operation of the V1, V2 and V3 valves. Debashis and Gopal [45] establish its model making some previous suppositions as the following: the heat transfer through the metal hydride layer takes place by one dimension conduction and the thermal properties of the metal hydride are constants during the system operation. In addition, the selection of the metal hydride's enthalpy formation is made so desorption and adsorption of the hydrogen happens with the solar irradiation level and cooling water temperature available. This is one of the main advantages of the metal hydride-based solar thermal water pumping systems. Debashis and Gopal [45] apply their model to a system located in the Indian region of Kolkata (22.8°N) with an aperture area of the solar system of 1 m^2. In this location the metal hydride temperature can vary between 21.85 °C and 61.85 °C and the pressure between 75 kPa y 250 kPa in a clear summer day. For a discharge head of 15 m the specific pumping rate is around 240 l/day and per kilogram of metal hydride in a clear summer day and 60 l/day and per kilogram of metal hydride in a cloudy winter day. As a consequence, the global efficiency of the pump varies between 1.5% and 0.6%. In addition to this information, Debashis and Gopal [45] make a parametric analysis as a function of the metal hydride layer width, intermediate cylinder volume, thermal conductivity of the metal hydride, external heat transfer coefficient, cooling temperature and enthalpy of formation of the metal hydride. One of the most interesting conclusions of this analysis is the following: if the metal hydride cost is much more than the land cost or the solar collector cost, is always more advantageous the use of a great number of solar collectors with thin metal hydride layer than only one solar collector with thick metal hydride layer. In relation to the cooling temperature, an optimal value exists since the decreasing of this temperature implies an increasing in the amount of pumped water per day but also the reduction of the system global efficiency. In the same way, an enthalpy of formation value exists that maximizes the amount of pumped water.

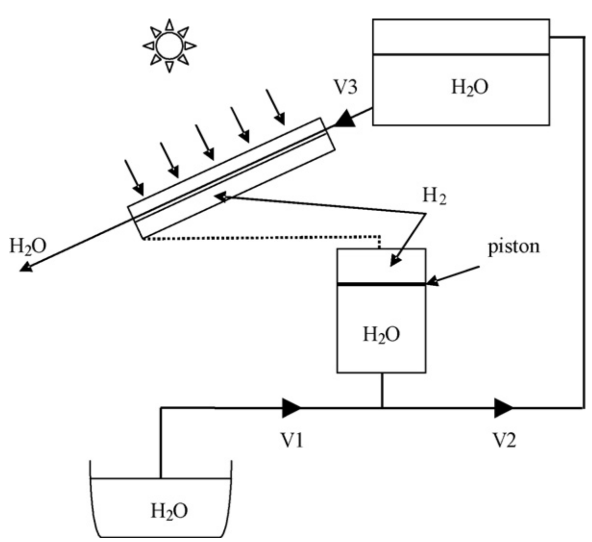

Fig. 10. Solar thermal metal hydride-based water pumping system of Debashis and Gopal [44].

Rajendra Prasad et al. [46,47] present another set of investigations similar to the former although, in principle, they do not treat the coupling of their proposed designs to any solar collector model. They just say that the proposed systems could be suitable for its coupling to waste or solar heat sources. In both cases, two different designs are simulated with mathematical models. One of them exhibits better characteristics for pumping small flow rates at important heights [46] while the other one is better for bigger flow rates and small heights [47]. The latter situation is more usual when it is about irrigation purpose pumping.

The design proposed by Rajendra Prasad et al. [46] is almost identical to the system of Solovey and Frolov [44] with the

exception of the solar collector presence. The global efficiency of this system is between 3% and 4% and the specific pumped flow rate per cycle is between 10 l/kg and 20 l/kg of metal hydride for discharge heads between 40 m and 100 m.

An innovative element in this kind of devices is introduced in the design proposed by Rajendra Prasad et al. [47]: a gear system. A mathematical model for the simulation of the system operation with the $LaNi_5$ alloy as hydrogen substratum is proposed. The model yields the following results: for an absorption temperature of 25 °C and a desorption pressure of 1000 kPa, an efficiency of 6% and specific flow rates of 60 l/kg, 80 l/kg and 130 l/kg of metal hydride per pumping cycle can be attained for discharge heads between 10 m and 20 m and desorption temperatures between 75 °C and 110 °C [47].

4. Conclusions

Knowledge about solar thermal heat engines for water pumping has been updated. New conventional designs have been added to previous known systems, some of them corresponding to solar thermal driven reverse osmosis desalination systems. It is pointed out the intensive activity on conventional designs in the 1970s and 1980s in the 20th century. In almost cases, these conventional systems are low power output and low efficiency systems: below 20 kW with the exception of the 150 kW solar Coolidge irrigation plant and below 5% respectively. In general, Rankine cycle with water or an organic substance as working fluid is used as power cycle to convert solar thermal energy into work.

In the case of unconventional systems, one additional vapour cycle-based system and some new liquid piston-based systems has been found in the literature. In addition, metal hydride-based systems for water pumping not covered by previous review papers have been introduced in this work as interesting water pumping devices. The power output and efficiencies of unconventional designs are even lower than conventional ones.

Acknowledgements

The author wishes to thank the Spanish Ministry for Education and Science (OSMOSOL project ENE2005-08381-C03-01) and the Council for Education, Culture and Sports of the Government of the Canary Islands (Spain) for funding this work.

References

[1] Bahadori MN. Solar water pumping. Sol Energy 1978;21:307–16.
[2] Delgado-Torres AM, García-Rodríguez L. Status of solar thermal-driven reverse osmosis desalination. Desalination 2007;216:242–51.
[3] Pytlinski JT. Solar energy installations for pumping irrigation water. Sol Energy 1978;21:255–62.
[4] Butti K, Perlin J. Un hilo dorado. 2500 años de arquitectura y tecnología solar, 1st ed., Madrid: Hermann Blume; 1985.
[5] Mankbadi RR, Ayad SS. Small-scale solar pumping: the technology. Energ Convers Manage 1988;28(2):171–84.
[6] Spencer LC. A comprehensive review of small solar-powered heat engines. Part I. A history of solar powered devices up to 1950. Sol Energy 1989;43(4):191–6.
[7] Spencer LC. A comprehensive review of small solar-powered heat engines. Part II. Research since 1950—"conventional" engines up to 100 kW. Sol Energy 1989;43(4):197–210.
[8] Spencer LC. A comprehensive review of small solar-powered heat engines. Part III. Research since 1950—"unconventional" engines up to 100 kW. Sol Energy 1989;43(4):211–25.
[9] Wong YW, Sumathy K. Solar thermal water pumping: a review. Renew Sust Energ Rev 1999;3:185–217.
[10] Delgado-Torres AM. Diseño preliminar de un sistema de desalación por ósmosis inversa mediante energía solar térmica. Academic thesis. Departamento de Física Fundamental y Experimental, Electrónica y Sistemas, University of La Laguna, 2006.
[11] Youm I, Sarr J, Sall M, Kane MM. Renewable energy activities in Senegal: a review. Renew Sust Energ Rev 2000;4:75–89.
[12] Zarza Moya E. Generación Directa de Vapor con Colectores Solares Cilindro Parabólicos, Proyecto DIrect Solar Steam (DISS). Academic thesis, Departamento de Ingeniería Energética y Mecánica de Fluidos, Seville University. 2003.
[13] Larson DL, Sands CD, Towle C, Fangmeier DD. Evaluation of solar energy for irrigation pumping. T ASAE 1978;21:110–5.
[14] Larson DL. Utilization of an on-farm solar powered pumping plant. T ASAE 1979;22:1106–14.
[15] Larson DL. Management of an on-farm grid connected solar thermal electric power plant. Appl Eng Agric 1986;2:228–33.
[16] Larson DL. Performance of the Coolidge solar thermal electric power plant. J Sol Energ T Asme 1987;109:2–8.
[17] Larson DL. Operational evaluation of the grid-connected Coolidge solar thermal electric power plant. Sol Energy 1987;38:11–24.
[18] Manolakos D, Papadakis G, Kyritsis S, Bouzianas K. Experimental evaluation of an autonomous low-temperature solar Rankine cycle system for reverse osmosis desalination. Desalination 2007;203:366–74.
[19] Spindler K, Chandwalker K, Hahne E. Small solar (thermal) water pumping system. Sol Energy 1996;57(1):69–76.
[20] Chandwalker K, Oppen MV. Solar power for irrigation. The small solar themal pump: an Indian development. Refocus 2001;2(4):24–6.
[21] Aghamohammadi M, Zarinchang J, Yaghoubi M. Performance of a Solar Water Pump in Southern of Iran, 2001; available at http://wrweb.com/escap-ngo-profiles/images-ngo-profiles/iran-solar-images/iran-solar-water-pump.pdf [last visit: March 26, 2004].
[22] Zeller B. Assessment of the economic performance of a solar thermal water pump for irrigation in semiarid India, 2003; available at http://www.troz.uni-hohenheim.de/research/Thesis/MScAES/Zellernew.pdf [last visit: March 26, 2004].
[23] Masson H, Girardier JP. Solar motors with flat-plate collectors. Sol Energy 1966;10(4):165–9.
[24] Burton R. A solar powered diaphragm pump. Sol Energy 1983;31(5):523–5.
[25] Rao DP, Rao KS. Solar water pump for lift irrigation. Sol Energy 1976;18:405–11.
[26] Jenness JR. Some considerations relative to a solar-powered savery water pump. Sol Energy 1961;5(2):58–60.
[27] Picken DJ, Seare KDR, Goto F. Design and development of a water piston solar powered steam pump. Sol Energy 1997;61(3):219–24.
[28] Sharma MP, Singh G. A low lift solar water pump. Sol Energy 1980;25:273–8.
[29] Al-Haddad AA, Enaya E, Fahim MA. Performance of a thermodynamic water pump. Appl Therm Eng 1996;16(4):321–34.
[30] Sudhakar K, Krishna MM, Rao DP. Analysis and simulation of a solar water pump for lift irrigation. Sol Energy 1980;24:71–82.
[31] Sumathy K, Venkatesh A, Sriramulu V. Thermodynamic analysis of a solar thermal water pump. Sol Energy 1996;57(2):155–61.
[32] Wong YW, Sumathy K. Thermodynamic analysis and optimization of a solar thermal water pump. Appl Therm Eng 2001;21:613–27.
[33] Sumathy K, Venkatesh A, Sriramulu V. A solar thermal water pump. Appl Energ 1996;53:235–43.
[34] Sumathy K, Venkatesh A, Sriramulu V. The importance of the condenser in a solar water pump. Energ Convers Manage 1995;36(12):1167–73.
[35] Sumathy K, Venkatesh A, Sriramulu V. Heat-transfer analysis of a flat-plate collector in a solar thermal pump. Energy 1994;19(9):983–91.

[36] Sumathy K, Venkatesh A, Sriramulu V. Experimental studies on heat transfer in the flat-plate collector of a solar pump. Renew Energ 1996;9:645–8.
[37] Wong YW, Sumathy K. Performance of a solar thermal water pump with n-pentane and ethyl ether as working fluids. Energ Convers Manage 2000;41:915–27.
[38] Wong YW, Sumathy K. Performance of a solar water pump with ethyl ether as working fluid. Renew Energ 2001;22:389–94.
[39] Quickenden TI, Hindmarsh KM, Teoh K. Experimental study of the Minto engine—A heat engine for converting low grade heat to mechanical energy. J Sol Energ T Asme 2004;126:661–7.
[40] Klüppel RP, Gurgel JMM. Thermodynamic cycle of a liquid piston pump. Renew Energ 1998;13(2):261–8.
[41] Klerk GB, Rallis CJ. A solar powered, back-to-back liquid piston Stirling engine for water pumping. J Energ S Afr 2002;13(2):36–42.
[42] Orda E, Mahkamov K. Development of ‘‘Low-tech’’ solar thermal water pumps for use in developing countries. J Sol Energ T Asme 2004;126:768–73.
[43] Northrup CJM, Heckes AA. A hydrogen—actuated pump. J Less Common Met 1980;74:419–26.
[44] Solovey AI, Frolov VP. Metal hydride heat pump for watering systems. Int J Hydrogen Energ 2001;26:707–9.
[45] Debashis D, Ram Gopal M. Studies on a metal hydride based solar water pump. Int J Hydrogen Energ 2004;29:103–12.
[46] Rajendra Prasad UA, Prakash Maiya M, Srinivasa Murthy S. Parametric studies on a heat operated metal hydride based water pumping system. Int J Hydrogen Energ 2003;28:429–36.
[47] Rajendra Prasad UA, Prakash Maiya M, Srinivasa Murthy S. Metal hydride water pumping system for low head—high discharge applications. Int J Hydrogen Energ 2004;29:501–8.